DIAPYCNAL MIXING, GRAVITY-CURRENT PROPAGATION AND SEDIMENT DISPERSION IN TURBULENT FLUIDS

Final Report for the ONR Contract No.
N00014-90-J-1598

by

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Department of Mechanical & Aerospace Engineering
Arizona State University
Tempe, AZ 85287-6106

Contract Period: January 01, 1990 - December 31, 1991

Contract Monitor: Dr. Alan Brandt

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1. Introduction:

During the contract period, the principal investigator and his post-doctoral associate Dr. Yign Noh worked on several different tasks. A major accomplishment was the completion of several laboratory and numerical studies on sediment dispersion in turbulent fluids, particularly in sediment-laden gravity currents and in estuarine benthic boundary layers. Some of the work started under the previous contact on turbulent mixing in stratified and rotating fluids was also completed. The work performed under these two categories are described below.

2. Research on Gravity Currents and Sediment Laden Turbulent Flows

2.1 Dispersion of suspended particles in turbulent flow

The upward dispersion of heavy particles in suspension in a turbulent flow was studied using a numerical model. The interaction between turbulence and particle diffusion leads to the formation of a horizontal front (or a 'lutocline'), across which the diffusion of particles and the propagation of turbulent energy are inhibited. However, as the settling velocity of the particles becomes larger or as the particle concentration becomes smaller, the interaction weakens thus suppressing the front formation. One-dimensional model equations for the problem were solved numerically to calculate the evolution of the particle concentration. A criterion for the formation of the front was proposed and the steady depth of the suspension layer was predicted.

2.2 Propagation of a Plume Along an Incline in the Presence of Boundary Mixing

The effects of boundary mixing on a continuous gravity current (a plume) propagating along an incline were investigated experimentally. Boundary mixing was generated by oscillating the incline along its plane. It was observed that, when the background turbulence is strong, such typical characteristics of the gravity current as its "raised-head" structure and sharp front disappear. Quantitative measurements of the frontal velocity, the density structure and the thickness of the gravity current were made and their dependencies on the intensity of turbulence at the boundary were determined.

2.3 Propagation of a Thermal in the Presence of Boundary Mixing

The effects of boundary mixing on the dispersion of suspended sediments along an incline were investigated using a laboratory experiment. A fixed volume of a negatively-buoyant substance (a suspension of aluminium particles or a saline solution) was introduced on a rough inclined plane, which was submerged in homogeneous water and was capable of making planar oscillations so as to produce turbulence. At weak turbulence intensities, the buoyant input flowed down the slope as a well-defined gravity current. As the turbulence intensity became stronger, however, it diffused away into the interior of the fluid. The frontal velocity of the gravity current, the density structure and the growth of the thickness of the buoyant cloud were measured, and their relations to the turbulence intensity at the boundary were obtained. A criterion which predicts the transition from gravity-current dominated transport to turbulent-diffusion dominated transport was found. A depth-averaged one dimensional model was developed to describe the flow, and its numerical solutions were compared with the experimental results. The model results were also used to evaluate the effects of the slope angle.

3. Research on Turbulent Mixing in Stratified Flows

3.1 Mixing in Stratified Turbulent Patches

Mixing in a turbulent patch, that was generated within a linearly stratified fluid of buoyancy frequency N_0, was studied experimentally. The turbulence within the patch was induced by sustained oscillations of a mono-planar grid. Grid oscillations produced a local turbulent region, which initially grows rapidly as in a non-stratified fluid and then assumes a quasi-stationary thickness $(L_p)_c$ when the stratification inhibits its vertical growth at a time $N_0 t \approx 4$. The growth beyond $(L_p)_c$ occurs slowly via breaking of interfacial waves at the entrainment interface. As mixing proceeds, the buoyancy frequency within the patch N decreases. The time evolution of N, the buoyancy lengthscale, the Thorpe lengthscale, the maximum Thorpe displacement, the overturning lengthscale and the available potential

energy fluctuations were measured and their relationships were investigated. Various aspects of the wave radiation from the patch to the outer stratified layer, the trapping of interfacial waves at the entrainment interface, and the effects of grid parameters on the evolution of patch were also studied.

3.2 The Evolution of an Isolated Turbulent Blob of Fluid in a Stratified Fluid

An experimental study was carried out on the evolution of an isolated turbulent region in an otherwise quiescent linearly stratified fluid. The turbulent patch was generated either by pulsed horizontal injection of a small volume of fluid, or by oscillating a horizontal grid in a stratified fluid for a fixed time interval to generate a localized mixed region. In the former case, the blob initially grows as in a non-stratified fluid for a non-dimensional time period of $Nt \approx 4\text{-}5$, attains a maximum height given by $h_m \simeq 0.67\,(V_0U_0^2/N^2)^{1/5}$ and then physically collapses slowly to form a quasi-horizontal dipole pattern; here V_0 is the volume discharged, U_0 is the discharge velocity and N is the buoyancy frequency. The time scale for the physical collapse of the blob was found to be much larger than that of the turbulence collapse. The evolutionary scenario of the oscillating-grid experiments was found to be somewhat different from its pulsed-jet counterpart. The patch initially grows in the vertical direction, attains a maximum height at $Nt \approx 4\text{-}6$ and then collapses to form an intrusion. If the grid-oscillation time is greater than this time scale, the 'lost' fluid from the patch into the intrusion is replenished by the return currents that are generated within the fluid. The energy of the internal waves generated during the collapse is distributed over a range of frequencies, but peaks at $\omega \approx (0.5 - 0.6)N$. Once the grid-forcing is stopped, the turbulence appears to decay at a time scale $Nt < 10$, but the inversions (and hence the non-zero Thorpe displacements) within the patch persist for much longer times. Simple theoretical models were presented to explain the evolution of turbulence for the cases considered and the experimental results were compared with the model predictions.

3.3 The Role of Molecular Diffusion on the Deepening of the Mixed Layer

Turbulent mixing across heat-stratified density interfaces was studied in the laboratory using oscillating-grid generated turbulence. The aim was to study the transition between the entrainment regimes dominated by interfacial-wave breaking and molecular diffusion, and to study the characteristics of the latter. It was observed that, above a critical Richardson number Ri_c, which depends on the Peclet number Pe, the mixing due to wave breaking disappears and that $Ri_c \sim Pe^{-n}$, where the mean value of the exponent n is approximately 1/2. Above Ri_c, the entrainment is molecular-diffusion dominated and takes place through a sequence of events: the buoyancy gradient of the initially sharp density interface is weakened by molecular diffusion until the mixed-layer eddies can engulf a portion of the interfacial layer wherefore the interface sharpens again. Thus, the entrainment events are recurrent with a rate-controlling diffusion stage between them. An entrainment law of the form $E \sim Ri^{-2}Pe^{-2}$, where E is the entrainment coefficient and Ri is the Richardson number, was suggested for the diffusion-dominated entrainment regime.

3.4 A numerical model for the fluid motion at a density front in the presence of background turbulence

The effects of background turbulence on gravity currents produced by lock exchange were investigated using a numerical model with the aim of understanding the fluid motions associated with coastal fronts. It is shown that, at high turbulence intensities, the mutual intrusion of gravity currents is inhibited and the horizontal mass transport is dominated by the turbulent diffusion. The propagation of the front, the horizontal density flux and the potential energy anomaly are calculated and are compared with available experimental data. The model is extended to include the effects of background rotation. It is found that, in the presence of background turbulence, the geostrophic equilibrium cannot be achieved, and the cross-frontal velocity persists indefinitely. The effects of rotation on the fluid motions were found to be impaired by the background turbulence.

3.5 A Numerical Study on the Formation of a Thermocline in Shear-Free Turbulence

The formation of a thermocline generated by the interaction between a stabilizing buoyancy flux and shear-free turbulence was studied using a numerical model. The time-evolutions of the vertical distributions of the buoyancy and turbulent kinetic energy were calculated and were used to evaluate the depth of the thermocline and the time required for its formation. The numerical results are compared with the results of previous laboratory experiments. The mechanisms, responsible for the formation of the thermocline are discussed in view of the numerical results.

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